On Throughput Analysis of the Mars In-situ ARQ Protocol

Robert Liang Bruce Kwan Cédric Florens
Jet Propulsion Laboratory
Pasadena, CA 91109

Abstract

Combating harsh and unpredictable channel environments is a part of the design of any in-situ communication system (i.e. rover to lander, rover to orbiter, etc.). Channel characteristics can range from simple additive white Gaussian noise (AWGN) channels to more bursty fading channels found in rover to orbiter links (i.e. canyon scenarios and typical orbiter passes around mountain ranges). A combination of forward error correction and automatic repeat request (ARQ) schemes are commonly used to provide a more robust communications link. ARQ enhances the communication link particularly for bursty fading channels.

Go-Back-N is a commonly used ARQ scheme and is an option in the newly developed Consultative Committee for Space Data Systems (CCSDS) Proximity-1 Link protocol [1], a data link layer protocol targeted specifically for in-situ applications. Optimization of frame sizes and retransmission persistence of the ARQ scheme require a good analytical model of how the scheme performs over various channel conditions.

In this paper, an analytical framework for modeling the COP-1 protocol is presented for both AWGN channels along with bursty fading channels. A Gilbert-Elliot two-state Markov model is used to model a bursty fading channel.

1 Introduction

ARQ protocols have not been prevalent in deep space missions. This has been the case because typical deep space missions only involved point to point links between an Earth-based Deep Space Network (DSN) station and a single spacecraft. The long propagation delays inherent in deep space links make retransmission protocols inefficient and impractical. However, recent missions have involved the build up of in-situ communications capabilities. The Mars '98 and Mars '01 orbiters will be responsible for relaying information from landed elements back to Earth. The in-situ links are over relatively short distances and consequently the cost of supporting ARQ is minimal.

The Mars '01 orbiter marks the beginning of the use of the newly developed CCSDS data link layer protocol, the Proximity-1 Link [1] protocol. The specification offers the option of reliable data stream support using the Go-Back-N protocol. In order to foster interoperability and to enable various space agencies to make use of the limited in-situ Mars communication resources, a number of other space agencies have also begun to sign on to the use of the Proximity Link-1 protocol. These include the European Space Agency's Mars Express Orbiter, U.K.'s Beagle 2 Lander, and CNES's Netlander missions. More recently, NASA's Mars Network effort has also committed to the use of the data link layer protocol as it builds up a constellation of six communication satellites for the purpose of supporting in-situ relay communications. These types of missions require robust communication despite the harsh and unpredictable channel environments. Channel characteristics can range from simple additive white Gaussian noise (AWGN) channels to more bursty fading channels found in rover to orbiter links (i.e., canyon scenarios and typical orbiter passes around mountain ranges). A combination of forward error correction (FEC) and automatic repeat request (ARQ) schemes are commonly used to provide a more robust or error free communication link. ARQ enhances the communication link particularly well for a bursty fading channel.

In this paper, an analytical framework is presented for modeling the ARQ scheme specified in the Proximity Linkl standard (COP-1) for AWGN channels and bursty fading channels. To be more specific, both the optimal frame size and retransmission persistence of the ARQ scheme are examined. In section 2, a background survey of the suite of relevant CCSDS protocols is provided. Section 3 contains a description of the propagation characteristics as well as Markov model of those characteristics. The analysis of ARQ over AWGN and Markovian channels is then presented in section 4 for specific scenarios (i.e., rover to lander, rover to orbiter). Lastly, conclusions are given in section 5.

2 CCSDS In-situ Protocols

2.1 Proximity Link-1

The Proximity Link-1 Space protocol was initially developed to facilitate interoperability across NASA projects as well as among international space missions. The specification [1] covers the physical layer, the medium access layer and the data link layer [4] and is aimed at supporting efficient space links between Earth remote proximity orbiters, landed elements, probes and other transmitting and receiving instruments that may be on the surface or in orbit.

The Proximity Link-1 standard provides support for two different grades of service (Sequence Controlled and Expedited). In Expedited mode, it is assumed that the higher layer protocols (i.e. Transport layer) will provide any of the necessary retransmission schemes. Consequently, the Expedited mode provides a single transmission of each frame of data. The Sequence Controlled service guarantees a reliable data stream without gaps or errors. The service is based on a Go-Back-N ARQ protocol. This service is called the Command Operations Procedure (COP). The COP-1 [6] was first defined for the CCSDS Telecommand [5] standard. A recent version of the COP, COP-P, has been developed specifically for use with the Proximity Link-1 protocol. The COP-P is simpler version of the COP-1 and provides fewer options. However, the basic protocol remains a Go-Back-N ARQ scheme.

2.2 Upper Layer Protocols

The CCSDS Proximity Link-1 protocol is a data link layer protocol. It has been designed for use with higher layer protocols such as the CCSDS File Delivery Protocol [7] and the CCSDS Space Communications Protocol Specification [8]. These higher layer protocols will provide other capabilities such as routing, end-to-end reliability, and application support (i.e. file transfers).

The CCSDS File Delivery Protocol (CFDP) is a monolithic store-and-forward transfer protocol designed for deep space relay communications. The protocol enables reliable file transfers, across multiple hops if necessary. CFDP handles lost transmissions and out-of-order packets. It has been designed to tolerate intermittent connectivity across deep space distances.

Space Communication Protocol Standards (SCPS) protocol stack specifies protocol layers 3-7 (network layer to application layer). The stack is based on TCP/IP but is robust against very long delays, high bit error rates, and intermittent connectivity. SCPS extends the reach of TCP to approximately lunar distances.

The effects of data link layer reliability on the higher layer protocols is important to understand in order to properly make use of the various protocol options. The interaction between ARQ protocols at the transport layer and the data link layer is one of the motivations for this current study and is also a topic of considerable interest in the commercial efforts to provide TCP/IP over wireless links [2].

3 Mars Propagation Models

3.1 Propagation Characteristics

Mars propagation models are now in development and are believed to be similar to Earth models. Specifically, large scale path loss due to reflection, diffraction, and scattering may be captured using classical propagation models (i.e. log-normal distributions).

Small scale propagation models due to multi-path (specular reflection, scattering) and velocity of the spacecraft elements may also be modeled using standard propagation models (i.e. Ricean distribution for line of sight communications and Raleigh distribution for non-line of sight communications).

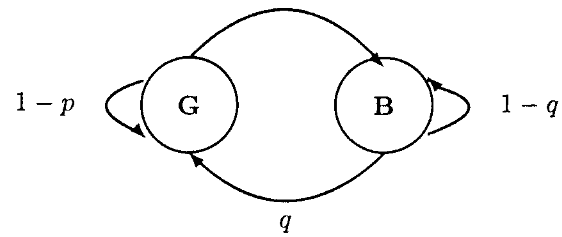

Figure 1: The Gilbert-Elliott channel model.

Periodic fading patterns may result depending on antenna patterns and the existence of specular reflections. For example, rover to orbiter communications may resemble land mobile satellite systems on Earth when the rover is traveling on slopes of smooth ground while attempting to transmit to an orbiter at low elevation angles. A parallel scenario was measured as a part of an INMARSAT experiment in Oregon where a mobile terminal was traveling in an area of rolling hills while attempting to communicate to a satellite. Large fades (up to 15dB) were experienced and was caused by a combination of the antenna pattern and the specular reflections due to the rolling hills. The periodicity of the fades and the duration of the fade and non-fade periods are dependent upon the operating frequency and the velocity of the elements relative to each other.

3.2 Hidden Markov Model

It is known according to the Mars propagation models that the communication channels between the rover, the lander, and the orbiter are subject to multi-path fading. This multi-path fading process (burst error) can be slowly varying depending on the speed of the rover, the speed of the spacecraft elements, the carrier frequency, and the actual physical scenario of the mission. The burst error propagation path can be modeled by using a stochastic process and can be expressed in the form of finite state Markovian model.

The finite state Markov chain has been used to model general time-varying channels with memory. The output from a finite state Markov channel depends on the present input and the channel state while the next channel state only depends on the present channel state and is independent of the input. The Gilbert-Elliott channel model [10] is a discrete-time, stationary, two state Markov chain as indicated in figure 1. One of the states is known as the good state; the other is known as the bad state. They are appropriately labeled by **G** and **B**. The probabilities that the channel state changes from **G** to **B** and from **B** to **G** are denoted by p and q. The state bit-error rates for **G** and **B** are E_g and E_b, respectively. Let **S** denote the state space of Markov model. Let

$$e = \begin{cases} 1 & \text{if a bit error occurred} \\ 0 & \text{otherwise.} \end{cases} \tag{1}$$

Let $\mathbf{X} = \{e\}$. It is observed that the sequence of the 2-tuples (s_1, e_1), (s_2, e_2), ... where $s_i \in \mathbf{S}$ and $e_i \in \mathbf{X}$ forms a Markov chain whose transition probabilities depend only on the previous state

$$p_{ij}(e) = Pr\{s_{t+1} = j, e_{t+1} = e | s_t = i\}. \quad (2)$$

The matrix $\mathbf{P}(e)$ which is constructed from $p_{ij}(e)$ is known as the observation (error) matrix. The probability transition matrix which governs the two state Markov model can be obtained as

$$\mathbf{A} = \sum_e \mathbf{P}(e). \quad (3)$$

If the bit error rate (BER) depends only on the current state and (2) is of the form

$$p_{ij}(e) = a_{ij} b_j(e), \quad (4)$$

then

$$\mathbf{P}(e) = \mathbf{A}\mathbf{B}(e) \quad (5)$$

where $\mathbf{B}$ is the diagonal matrix of the state error probabilities. This type of model is referred to as the hidden Markov model because the Markov states are not directly observable [11] [10]. Let π be a row vector representing the steady state Markov states probability distribution. For Gilbert-Elliott model we have

$$\mathbf{A} = \begin{pmatrix} 1-p & p \\ q & 1-q \end{pmatrix}, \quad (6)$$

$$\mathbf{B}(0) = \begin{pmatrix} 1-E_g & 0 \\ 0 & 1-E_b \end{pmatrix}, \quad (7)$$

and

$$\mathbf{B}(1) = \begin{pmatrix} E_g & 0 \\ 0 & E_b \end{pmatrix}. \quad (8)$$

The observation or the error matrix of Gilbert-Elliott model can be expressed as

$$\mathbf{P}(0) = \begin{pmatrix} (1-p)(1-E_g) & p(1-E_b) \\ q(1-E_g) & (1-q)(1-E_b) \end{pmatrix}, \quad (9)$$

and

$$\mathbf{P}(1) = \begin{pmatrix} (1-p)E_g & pE_b \\ qE_g & (1-q)E_b \end{pmatrix}. \quad (10)$$

The steady state probability distribution of Gilbert-Elliott model is given by

$$\pi = \begin{pmatrix} \frac{q}{p+q} & \frac{p}{p+q} \end{pmatrix}. \quad (11)$$

To model error sources in full duplex channel with a hidden Markov model, Turin [11] has defined

$$\mathbf{e} = \begin{pmatrix} e^{(1)} & e^{(2)} \end{pmatrix} \quad (12)$$

to characterize errors in the forward and feedback channels. $e^{(i)} = 1$ if a bit error occurred and $e^{(i)} = 0$ otherwise, i = 1 and i = 2 correspond to the forward and feedback channels, respectively. It has shown if error sources in both channels are independent and described by the hidden Markov parameters $\pi^i, \mathbf{P}_i(e^{(i)})$, i = 1, 2, the composite model parameters for both forward and feedback channels are the Kronecker products of the component model parameter matrices.

In a pure ARQ protocol the message sequence is broken up into packets of length k. Each of these packets is encoded using a binary linear detection code **C** with length n. The most frequently used error detection codes are CRC codes. Since the bit-level channel error models do not depend on the communication system parameters, it is important to find the relationship between the block-error and bit-error models. For additive white Gaussian noise (AWGN) bit-level model with a fixed BER, the block error rate (BLER) is

$$\begin{aligned} BLER &= 1-(1-BER)^M \\ &\simeq 1-exp(-M\,BER) \text{ for M BER} \ll 1, \end{aligned} \quad (13)$$

where M is the data block size. For Gilbert-Elliot bit-level model, as indicated in figure 1, the block error rate is

$$BLER = 1 - \pi \begin{pmatrix} (1-p)(1-E_g) & p(1-E_b) \\ q(1-E_g) & (1-q)(1-E_b) \end{pmatrix}^M \mathbf{1} \quad (14)$$

where π is defined in equation (11) and $\mathbf{1}$ is a vector of ones.

4 ARQ

Error detection and retransmission are invariably a user defined service, forming parts of the newly developed CCSDS Proximity-1 Link Protocol [1]. Combinations of the error detection and retransmission allow the user to send and receive data with a greatly reduced probability of error. Cyclic Redundancy Code (CRC) can be used for variable frame length error detection; Reed-Solomon code is used for fixed frame length error detection and correction. For in-situ communication systems it is often not sufficient simply to detect an error; it must be corrected. A popular technique for this correction is the retransmission approach. The usual technique for obtaining a retransmission is for the receiving node (data link control layer) to send an acknowledgment (ACK) signal to the transmitting node (data link control layer) when it receives an error-free data frame. If an error is detected then a negative acknowledgment (NAK) signal is send, the NAK signal triggers a retransmission of the erroneous data frame. This type of retransmission schemes are known as automatic repeat request (ARQ) schemes.

4.1 Overview

For those packets entering data link control (DLC) layer from the network layer, a header is appended to each packet to form a frame and frames are sent to the physical layer for transmission. The CCSDS Proximity-1 Link Protocol [1] uses a version 3 transfer frame which encompasses 5 bytes of mandatory transfer header and a transfer frame data field. The maximum length of the transfer frame is 2048 bytes. In addition, 3 bytes of attached synchronization marker and 4 bytes of attached CRC generator polynomial are used to provide frame synchronization and error detection. There are three basic types of retransmission protocol. They are stop-and-wait (SW) ARQ, go-back-N (GBN) ARQ, and selective repeat (SR) ARQ.

In the SW ARQ, the transmitter sends out a frame and waits for an acknowledgment. Once the receiver has received the frame, it would respond by sending an ACK if the data packet was deemed error-free, or it would send a NAK if the data packet contains a detectable error. Once the transmitter receives the acknowledgment from the receiver, it would retransmit the data packet if the acknowledgment is a NAK, or it would transmit a new data packet.

The SW ARQ scheme is clearly inefficient since the transmitter is idle while waiting for the acknowledgment. To alleviate this problem of inefficiency, the transmitter may send a series of sequentially numbered frames. While no errors occur, the receiver sends an ACK. The receiver sends a NAK if the data packet contains detectable errors. The receiver would discard that erroneous frame and all future incoming frames until the frame with detectable errors is correctly received. Thus, the transmitter must retransmit the frame in error plus all succeeding frames that were transmitted in the interim. This approach is known as GBN ARQ.

With SR ARQ, the only retransmitting frames are those which have received a NAK or those whose time out has occurred. SR ARQ is more efficient than SW ARQ and GBN ARQ because the amount of retransmissions is minimized. However, in order to implement SR ARQ the receiver must maintain a buffer large enough to save all post-NAK frames until the frame in error is retransmitted. Furthermore, the receiver must contain logic and processing power to reinsert that frame in the proper sequence. Due to the complexity of implementations, SR ARQ is much less popular than GBN ARQ. GBN ARQ is an option in the CCSDS Proximity-1 Link Protocol [1]. In the following sections, the performance of the GBN ARQ is examined.

4.2 Throughput Analysis over AWGN Channels

There are two basic measures by which ARQ is evaluated: reliability and throughput. In ARQ systems it expresses reliability in terms of the accepted packet error rate. That is the percentage of the packets accepted by the receiver that contain errors. It is clear that the accepted packet error rate is function of the error detection code. A packet is erroneously accepted if on any transmission attempt, it contains an undetectable error pattern. For the CCSDS Proximity-1 Link Protocol CRC is used for variable frame length error detection; Reed-Solomon code is used for fixed frame length error detection and correction. For both cases the probability of undetectable errors is negligible. Thus, the probability of detectable error (or equivalently, the probability of retransmission) is approximately equal to the $BLER$ in (13) or (14).

For GBN ARQ the available data frames are continuously transmitted without waiting for an ACK. On receipt of a NAK or the expiration of the timeout without receiving an ACK or a NAK, the frame in question and all following frames are retransmitted. Let us assume the channel noise is independent and identical distributed. In addition, we assume that the transmitting DLC is in a saturated state. It means that the transmitter always has at least one frame waiting for transmission. Moreover, the transmission process of GBN ARQ is disjoint in time. Thus, the transmission process is governed by a renew-process. This implies to find the average amount of time it takes to successfully transmit a data packet is equivalent to find the average stopping time of the renew-process. For AWGN channel, the average stopping time is merely

$$t_s = t_I \left\{ \frac{1 + (a-1)BLER}{1 - BLER} \right\} \tag{15}$$

where t_I is the minimum time between transmissions, $a = \frac{t_T}{T_I}$, and BLER is specified in (13). The maximum possible throughput of GBN ARQ is

$$\lambda_{max} = \frac{1}{t_s}. \tag{16}$$

The normalized throughput, [17] and [16], with perfect acknowledgment is

$$\eta = \lambda_{max} t_I = \frac{1 - BLER}{1 + (a-1)BLER}. \tag{17}$$

Let l denote the length of the data field, and let l' denotes the length of the control field (i.e., the control field includes AMS, the frame header information, and 32 bits CRC). From equation (13) it is clear that the block error rate, $BLER$, is a function of the frame size (i.e., $M = l + l'$) and the channel condition which is represented by the bit error model, BER. The actual delivered data volume is a function of the retransmission probability, namely, BLER. The actual delivered data rate is defined to the amount of data which are successfully delivered to the receiving node over the average stopping time, t_s. Then the actual delivered data rate $D = \lambda_{max} l$, and $t_I = \frac{l+l'}{C}$ where C is the forward link transmission rate capacity in bits per second. Then

$$\frac{D}{C} = \left(\frac{l}{l + l'} \right) \left(\frac{1 - BLER}{1 + (a-1)BLER} \right). \tag{18}$$

The link transmission rate capacity, C, is a fixed value in equation (18). The Proximity-1 link [1] and Mars Network [9] support 11 forward and return data rates as indicated below

$$C = 2^i \ \text{kbps} \qquad \text{for i} = 1, 2, ..., 11. \tag{19}$$

Figure 3 is plot of the normalized data rate, $\frac{D}{C}$, as a function of the data packet size in bits for $BER = 10^{-5}$, $BER = 10^{-6}$, and $BER = 10^{-7}$ with C = 256 kbps. It is apparent that if the data packet length, l, is small, the system is operating inefficiently. For example, the link is transmitting the overhead rather than real data. On other hand, if the data packet size, l, is too large, the retransmission probability, BLER, increases. This effectively reduces the throughput of the system. Thus, there exists an optimal data packet size in the sense of maximizing the delivered data rate,

$$l^* = arg\{\max_l \left(\frac{l}{l + l'} \right) \left(\frac{1 - BLER}{1 + (a-1)BLER} \right)\}. \tag{20}$$

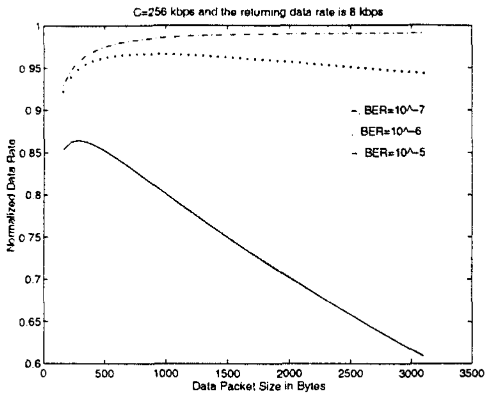

Figure 2: Delivered data rate efficiency of GBN ARQ vs. CCSDS Proximity link data packet size.

4.2.1 Rover to Lander

Denote the forward and the return link transmission rate capacities by C_f and C_r, respectively. Assume that the transmission delay is negligible in the case of the rover to the lander communication. CRC is used to provide error detections. The optimal data field length and normalized throughput efficiency are tabulated in tables 1 to 5 for $BER = 10^{-5}$, $BER = 10^{-6}$, and $BER = 10^{-7}$ and various C_f and C_r. From these tables it is apparent that the data field length increases as the BER decreases. This is consistent with intuitions. As the BER decreases, the $BLER$ also decreases. This implies that the probability of retransmission decreases. Thus, in order for the channel becomes more efficient, the transmitting DLC must increase the data field length to reduce the overall overhead.

From figure 3 it is observed that the performance degradation of normalized throughput is small for data field length which is greater than the optimal data field length when $BER = 10^{-6}$ and $BER = 10^{-7}$. For example, $\frac{D}{C_f} = 0.96743$ with $l = 865$, $\frac{D}{C_f} = 0.96637$ with $l = 1024$, and $\frac{D}{C_f} = 0.95652$ with $l = 2043$ when $BER = 10^{-6}$. There is only one percentage of throughput degradation when $l = 2043$ comparing with $l = 865$. This implies for small BER the system throughput is dominated by the data overhead in the transfer frame since the retransmission probability is small. However, it is also observed that the performance degradation becomes significant for $BER = 10^{-5}$ when the transfer data packet size varies from the optimal value, 277 bytes. For example, $\frac{D}{C} = 0.86432$ with $l = 277$, $\frac{D}{C} = 0.79912$ with $l = 1024$, and $\frac{D}{C} = 0.69807$ with $l = 2043$. There is roughly 20 percent of throughput degradation when $l = 2043$ comparing with $l = 277$. This implies for relatively large BER the system throughput is dominant by the retransmission probability.

As we have mentioned above there are two measures by which ARQ is evaluated. One is the reliability, and the other is the throughput. The performance of one of the measures can be increased at the expense of the other one. In the following example, we will compare the free-transmission (no retransmission) scheme with GBN ARQ. We assume that if an error in the transfer frame is detected then the whole frame is dropped (i.e., no retransmission). Tables 6 and 7 list the normalized delivered data rate at various data packet sizes for both free-transmission and GBN ARQ for $BER = 10^{-5}$ and $BER = 10^{-6}$, respectively. With $BER = 10^{-7}$, the optimal data field length is 2733 bytes for GBN ARQ and the maximum normalized efficiency is 0.9907. With $BER = 10^{-7}$, the optimal data packet size is 3861 bytes for free-transmission and the maximum normalized efficiency is 0.9938. From these results it is apparent that the normalized throughput for the free-transmission is more efficient than the GBN ARQ scheme. However, the free-transmission delivers data with gaps (i.e., erroneous frames are dropped) while the GBN ARQ scheme delivers data without gaps and errors.

4.2.2 Rover to Orbiter

We assume that the forward data rate, C_f is 256 kbps and the returning date rate, C_r, is 8 kbps. CRC is used to provide error detections. Furthermore, we assume 10 minutes of Orbiter pass, and the distance between the obiter and the rover is 800 km. Let q denote the maximum number of retransmission (as specified in COP-P). For example, there is no retransmission when $q = 0$; GBN ARQ is implemented when $q = \infty$. Assume the rover is in a saturated transmission state. That is that the rover always has at least one frame waiting for transmission. Let

$$
\begin{aligned}
T_s &= \text{the amount of time that a particular frame, } \mathbf{f}\text{, uses the channel,} \\
S &= \text{the event that } \mathbf{f} \text{ is successfully transmitted,} \\
F &= \text{the event that the frame } \mathbf{f} \text{ is dropped,} \\
P_B &= BLER \text{ as specified in equation (13),} \\
P_f &= P_B^q \text{ where } P_f \text{ is the frame drop probability.}
\end{aligned}
$$

Then,

$$\mathbf{E}\{T_s|S\} = t_I + (1 - P_B)\sum_{i=1}^{q-1} iP_B^i t_T, \tag{21}$$

where t_I and t_T are specified in equation (15). Furthermore,

$$\mathbf{E}\{T_s|F\} = (q-1)t_T. \tag{22}$$

Therefore,

$$
\begin{aligned}
\mathbf{E}\{T_s\} \;=\; & (q-1)P_f t_T + (1 - P_f)t_I + P_B t_T \\
& \{1 + (q-1)P_B^q - qP_B^{q-1}\}\frac{1 - P_f}{1 - P_B}.
\end{aligned} \tag{23}
$$

$\mathbf{E}\{T_s\}$ is the average amount of time that a distinct data frame uses the channel. This particular frame is successfully delivered with probability $1 - P_f$. Therefore, the total delivered data volumes over 10 minutes Obiter pass and the frame error rates can be easily computed. Results (using optimal data field length) for $q = 0$, $q = 2$, $q = 4$, $q = 8$, and $q = \infty$ are tabulated in tables 8 and 9 for $BER = 10^{-5}$ and $BER = 10^{-6}$, respectively. From these results, it can be easily seen there is a diminished return in term of data volume as q increases. This is simply because the frame error rate (or the retransmission probability) dramatically decreases as q increases.

For a given channel condition (i.e., BER), ARQ with $q = \infty$ provides error free data delivery at the expense of possibly long delays. Therefore in practice a data frame may be transmitted at most a finite number of times, q, depending on the Quality of Service (QoS) as specified in COP-P. Different choices of q allow to trade off between transmission latency and the frame drop probability. The resulting protocol is sometimes referred as q-persistent GBN ARQ protocol. In this section we are interested in evaluating the effect of limiting the maximum number of retransmissions or q on the throughput performance of the system over AWGN channel. We assume that the forward channel is identically independent distributed AWGN channel. The backward channel is error free since the backward channel operates at very low data rates comparing with forward channel. Let τ denote the number of times that the channel has been used between two successful transmissions. The throughput η is then defined as the inverse of the expected value of τ. τ is one time unit if the data packet gets acknowledged after its first transmission. This event happens with probability $1-P_f$. Further τ is N+1 if the data packet gets acknowledged after its second transmission. That last event happens with probability $P_f(1-P_f)$. The following table gives the possible transmission durations with the corresponding occurrence probabilities for q-persistent GBN ARQ.

count	τ	$P_r(\tau)$
0	1	$1-P_f$
1	$N+1$	$P_f(1-P_f)$
...	...	...
$q-1$	$(q-1)N+1$	$P_f^{q-1}(1-P_f)$
q	$(q-1)N+2$	$P_f^q(1-P_f)$
$q+1$	$qN+2$	$P_f^{q+1}(1-P_f)$
...	...	...

Hence the expected value of τ is

$$E(\tau) = \sum_{\tau} \tau P_r(\tau) = \sum_{k=0}^{\infty}(kN+1)P_f^k(1-P_f) + \sum_{m=0}^{\infty} \sum_{k=mq}^{(m+1)q-1} m(1-N)P_f^k(1-P_f).$$

It can be shown that

$$E(\tau) = \frac{NP_f + 1 - P_f}{1-P_f} + \frac{q(1-N)P_f^{2q-1}}{1-P_f^q}. \tag{24}$$

In figure 3 the normalized throughput as defined in section 4.2 is plotted for q-persistent GBN as a function of the data length. BER was chosen high enough (i.e. $BER = 10^{-2}$) to see behaviors of the curves as q increases. When BER is low, very few retransmissions occur. The throughput of infinite persistent GBN is close to the one of q-persistent GBN. As BER increases these curves tend to detach from each other more and more. In figure 4 the maximum normalized throughput is plotted as a function of q for $BER = 10^{-2}$. It is observed that the maximum normalized throughput decreases as q increases.

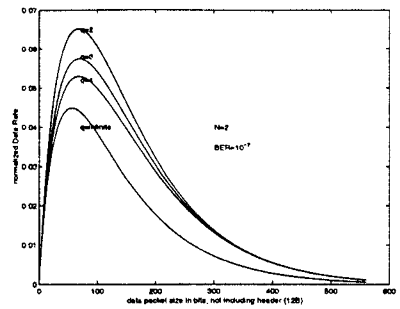

Figure 3: Delivered data rate efficiency of p-persistent GBN ARQ (N=2) vs. CCSDS Proximity link data packet size.

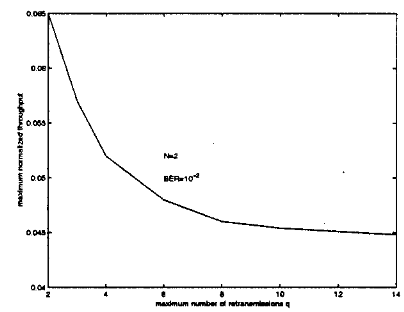

Figure 4: Maximum delivered data rate of p-persistent GBN ARQ (N=2) vs. maximum number of retransmissions, q.

4.3 Throughput Analysis over Markov Channels

ARQ protocols have not been prevalent in deep space missions because of the long propagation delay. Traditionally, forward error control (FEC) has been used to overcome channel errors in deep space missions. However in a highly bursty (i.e., fast fading) in-situ communication environment, complex FEC can be wasteful proposition in terms of system capacity performance and there is considerable encoding and decoding complexities as well. ARQ can be more efficient provided that the delay introduced by retransmissions is acceptable. In other

Table 2. Optimal Data Packet Size With $C = C_f = 8kbps$.

BER	Efficiency	Optimal Data Packet Size (bytes)
10^{-5}	0.91396	272
10^{-6}	0.97244	863
10^{-7}	0.99125	2733

Table 3. Optimal Data Packet Size With C = 32 kbps and C_f = 8 kbps.

BER	Efficiency	Optimal Data Packet Size (bytes)
10^{-5}	0.90891	272
10^{-6}	0.97188	863
10^{-7}	0.99119	2733

Table 4. Optimal Data Packet Size With C = 64 kbps and C_f = 8 kbps.

BER	Efficiency	Optimal Data Packet Size (bytes)
10^{-5}	0.90226	272
10^{-6}	0.97115	864
10^{-7}	0.99112	2733

Table 5. Optimal Data Packet Size With C = 128 kbps and C_f = 8 kbps.

BER	Efficiency	Optimal Data Packet Size (bytes)
10^{-5}	0.89248	274
10^{-6}	0.96967	864
10^{-7}	0.99097	2733

Table 6.Throughput Comparison of ARQ With Free-Transmission ($BER = 10^{-5}$).

$\frac{D}{C}$ of GBN ARQ (N=2)	$\frac{D}{C}$ of Free-Trans.	Data Packet Size in bytes
0.864323	0.9366	277 (Optimal for ARQ)
0.860756	0.9395	381 (Optimal for Free-Trans.)
0.790024	0.9098	1024
0.698073	0.8434	2043

Table 7.Throughput Comparison of ARQ With Free-Transmission ($BER = 10^{-6}$).

$\frac{D}{C}$ of GBN ARQ (N=2)	$\frac{D}{C}$ of Free-Trans.	Data Packet Size in bytes
0.9674	0.9794	865 (Optimal for ARQ)
0.9664	0.9803	1024
0.9651	0.9805	1218 (Optimal for Free-Trans.)
0.9565	0.9780	2043

Table 8. $BER = 10^{-5}$, 10 min. Orbiter Pass, the length of data field is l^*

Transmission Type	Data Volume (M bits)	Frame Error Rate
Free Trans.	144.307	3.0951×10^{-2}
$q = 2$	131.766	1.1938×10^{-5}
$q = 4$	131.128	6.2346×10^{-6}
$q = 8$	131.127	1.7013×10^{-15}
$q = \infty$	131.127	0

Table 8. $BER = 10^{-6}$, 10 min. Orbiter Pass, the length of data field is l^*

Transmission Type	Data Volume (M bits)	Frame Error Rate
Free Trans.	150.605	9.7917×10^{-3}
$q = 2$	148.336	6.6209×10^{-7}
$q = 4$	148.293	5.0296×10^{-11}
$q = 8$	148.293	2.9024×10^{-19}
$q = \infty$	148.293	0

Table 9. C_f = 128 kbps, C_r = 8 kbps, p = 0.02, q = 0.97 and $E_b = 10^{-4}$

BER	Efficiency	Optimal Data Packet Size (bytes)
10^{-5}	0.8535	247
10^{-6}	0.9370	496
10^{-7}	0.9488	590

words, ARQ schemes allow us to trade a decreasing frame dropped probability for a larger maximum tolerable delay to meet different traffic QoS requirements.

There have been enormous interest in analyzing the performance of various types of ARQ in Gilbert channel model [18] to [21]. Gilbert model is a two state Markov model. This model can be used to characterize the frame error for fixed length data frames. Recently, Turin [11] has studied the performance of ARQ in Gilbert-Elliott model. Gilbert-Elliott model can be used to model bit error sequence and this model is independent of the communication parameters such as data transfer frame size. Results presented in the table 9 are based on his approach. We assumed $p = 0.02$ and $q = 0.97$ with $E_b = 10^{-4}$ in the Gilbert-Elliott model in the figure 1. With these parameters, it represents that the channel is in Good state 98 percent of the time and the channel is in Bad state 2 percent of the time. Maximum normalized throughputs and optimal data block (or field) sizes are tabulated in table 9.

5 Conclusion

In this paper the performance of the COP (GBN ARQ) protocol is presented for both AWGN channels along with bursty fading channels. There are two basic measures by which ARQ is evaluated. One is the reliability and the other is efficiency. ARQ schemes allow us to trade one measure for the other one to meet different traffic QoS requirements. The optimal data frame sizes are obtained for AWGN with various BER along with Gilbert-Elliott channel model. The maximum data returns with and without ARQ for 10 minutes Obiter pass are presented for AWGN channels.

Further directions of this study include extensions to more elaborate ARQ protocols such as selective repeat ARQ, selective repeat GBN ARQ, and code diversity combining schemes. In addition we would like to examine the performance of GBN ARQ with Mars propagation model.

6 Acknowledgment

The research described in this paper was carried out in part by the Jet Propulsion Laboratory, California Institute of Technology under a contract with the National Aeronautics and Space Administration.

References

[1] *Proximity-1 Space Link Protocol.* Recommendation for Space Data Systems Standards, CCSDS 211.0-X-X, red book-1 edition, July 1999.

[2] Reiner Ludwig and Almudena Konrad and Anthony D. Joseph and Randy H. Katz. *Optimizing the End-to-End Performance of Reliable Flows over Wireless Links. Proceedings of ACM/IEEE MobiCom 99.*

[3] *UHF Transceiver Model C/TT-505: Theory of Operation/User's Manual.* Cincinatti Electronics Corp., , April 1999.

Table 1. Optimal Data Packet Size With C = 256 kbps and C_f = 8 kbps.

BER	Efficiency	Optimal Data Packet Size (bytes)
10^{-5}	0.8643	277
10^{-6}	0.9667	865
10^{-7}	0.9907	2733

[4] *Information Technology-Open Systems Interconnection-Basic Reference Model: The Basic Model.* International Standard, ISO/IEC 7498-1", 2nd Edition, 1999.

[5] *Telecommand Part 2 - Data Routing Service* Recommendation for Space Data Systems Standards, CCSDS 202.0-B-2, Blue Book, 2nd Issue, November, 1992.

[6] *Telecommand Part 2.1 - Command Operation Procedures*, Recommendation for Space Data Systems Standards, CCSDS 202.0-B-1, Blue Book, 2nd Issue, October, 1991.

[7] *File Delivery Protocol*, Recommendation for Space Data Systems Standards, CCSDS XXXX.

[8] *Space Communication Protocol Specification*, Recommendation for Space Data Systems Standards, CCSDS XXXX.

[9] *Mars Network Requirements: A Communications and Navigation System at Mars*, Draft Document, 9/1/99.

[10] W. Turin. *Digital Transmission System: Performance Analysis and Modeling*, McGraw-Hill, second edition, 1999.

[11] W. Turin. Throughput analysis of the go-back-n protocol in fading radio channels, *IEEE Journal on Selected Areas in Communications*, 17(5):881–887, May 1999.

[12] L. Wilhelmsson and L. Mlstein. On the Effect of Imperfect Interleaving for the Gilbert-Elliott Channel, *IEEE Trans. on Comm*, Vol. 47, No. 5, pp. 681-688, May 1999.

[13] J. Goldhirsh and W. Vogel. *Handbook of Propagation Effects for Vehicular and Personal Mobil Satellite System* APL Technical Report A2a-98-U-0-021, December 1998.

[14] D. Bertsekas and R. Gallager. *Data Networks* Prentice Hall, 2nd Edition, 1992.

[15] S. Wicker. *Error Control System for Digital Communication and Storage*, Prentice Hall, 1995.

[16] W. Stalling. *High-Speed Networks: TCP/IP and ATM Design Principle*, Prentice Hall, 1998.

[17] M. Schwartz. *Telecommunication Networks: Protocal, Modeling, and Analysis* Addison-Wesley Publishing Co., 1987.

[18] S. R. Kim and C. K. Un. Throughput Analysis for Two ARQ Schemes Using Combined Transition Matrix, *IEEE Trans. on Comm*, Vol. 40, No. 11, pp. 1679-1683, Nov 1992.

[19] D. Lu and J. Chang. Analysis of ARQ Protocols via Signal Flow Gragphs, *IEEE Trans. on Comm*, Vol. 37, No. 3, pp. 245-251, March 1989.

[20] Y. Cho and C. Un. Performance Analysis of ARQ Error Controls under Markovian Block Error Pattern, *IEEE Trans. on Comm*, Vol. 42, No. 2, pp. 2051-2061, Feb. 1994.

[21] C. Leung, Y. Kikumoto, and A. Sorrensen. The throughput Efficiency of the Go-Back-N ARQ Schemes Under Markov and Related Error Structures, *IEEE Trans. on Comm*, Vol. 36, No. 2, pp. 231-234, Feb. 1988.